REPORT No. 402

EFFECT OF ORIFICE LENGTH-DIAMETER RATIO ON FUEL SPRAYS FOR COMPRESSION-IGNITION ENGINES

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SUMMARY

Experimental results on the effect of the length-diameter ratio of the orifice on the spray characteristics, together with a brief analysis of the factors affecting these characteristics, are presented in this report. The length-diameter ratios tested ranged from 0.5 to 10; the orifice diameters from 0.008 to 0.040 inch; and the injection pressures from 2,000 to 8,000 pounds per square inch. The density of the air into which the fuel was discharged was varied from 0.38 to 1.35 pounds per cubic foot.

When a plain stem was used in the injection valve and the length-diameter ratio of the orifice was increased from 0.5 to 10, the rate of spray-tip penetration at first decreased and reached a minimum between the ratios of 1.5 and 2.5; then reached a maximum between the ratios of 4 and 6; and decreased again as the ratio was increased to 10. The exact position of the maximum and minimum points depended upon the orifice diameter. The spray cone angle was affected very little by the variation of either the diameter of the orifice or the length-diameter ratio tested at ratios greater than 4.

With a helically grooved stem in the injection valve the ratios at which the highest penetration occurred varied between 5 and 7. The spray cone angle increased with the ratio of the orifice area to groove area.

INTRODUCTION

One of the methods by which a designer of high-speed compression-ignition engines can control the penetration and cone angle of the fuel spray in the combustion chamber is to vary the geometrical shape of the discharge nozzle. A considerable amount of work has been done to determine the difference in the kind of sprays from differently designed discharge nozzles. Little consideration has been given, however, to the effect on spray characteristics of the variation of the orifice length in relation to its diameter. The usual practice is to use a length of orifice two or three times the diameter.

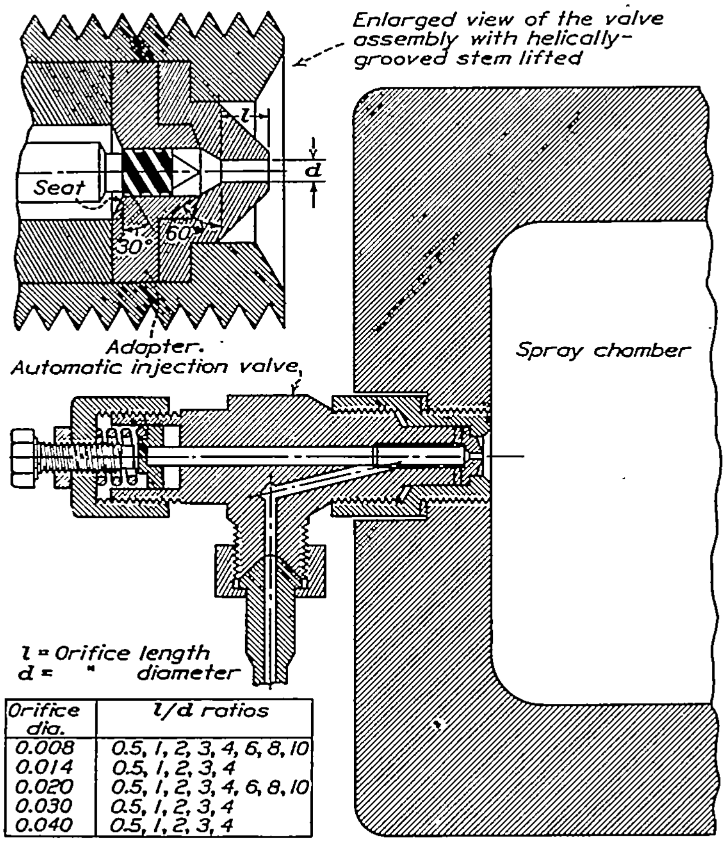
The results of a preliminary investigation at this laboratory on the effect of orifice length-diameter ratio on penetration, spray cone angle, and coefficient of discharge with a 0.014 and a 0.040 inch diameter orifice with ratios from 0.5 to 4 have already been published. (References 1 and 2.) This work demonstrated that when a plain stem was used in the injection valve an increase in the ratio caused the spray-tip penetration first to decrease, reaching a minimum between the ratios 1.5 and 2.5, and then to increase with the trend of the curves, indicating a maximum at a ratio greater than 3.5. The exact ratio at which a maximum was reached could not be definitely determined because the range of ratios tested was too small. The results of these tests pointed to the need for extending the investigation to include a greater range of orifice length-diameter ratios. The work was therefore continued with two other nozzles having single orifices of 0.008 and 0.020 inch diameter and ratios from 0.5 to 10. Tests were also made with a 0.030-inch orifice having ratios from 0.5 to 4. The tests were conducted at the Langley Memorial Aeronautical Laboratory at Langley Field, Va.

METHODS AND APPARATUS

The general method employed in this investigation was to take high-speed motion pictures of individual fuel sprays discharged from the nozzle into air at various densities and at room temperature. The pictures were taken with the N. A. C. A. spray-photography equipment described in reference 3.

A plain injection-valve stem and one with four grooves, having a helix angle of 30°, were tested in conjunction with the nozzles. A cross section of the assembled valve showing the two stems and the shape of the nozzle is shown in Figure 1. In the table accompanying the figure the size of orifice for each nozzle and the length-diameter ratios are given. The combined area of the grooves in the helically grooved stem was equivalent to a 0.022-inch diameter orifice, which made the ratio of orifice area to groove area 0.2, 0.4, 0.9, 1.9, and 3.3 for the orifices having the following respective diameters: 0.008, 0.014, 0.020, 0.030, and 0.040 inch.

The injection pressures were varied from 2,000 to 8,000 pounds per square inch. The chamber air densities in the tests with the 0.014 and 0.040 inch orifices were varied from 0.38 to 1.35 pounds per cubic foot, corresponding to chamber pressures of 60 to 250 pounds per square inch at room temperature. The air density in the tests with the 0.008, 0.020, and 0.030 inch diameter orifices was 0.99 pound per cubic foot, corresponding to a chamber pressure of 180 pounds per square inch at room temperature. A high grade



Orifice dia.	l/d ratios
0.008	0.5, 1, 2, 3, 4, 6, 8, 10
0.014	0.5, 1, 2, 3, 4
0.020	0.5, 1, 2, 3, 4, 6, 8, 10
0.030	0.5, 1, 2, 3, 4
0.040	0.5, 1, 2, 3, 4

FIGURE 1.—Injection valve assemblies. Orifice sizes and ratios tested

of Diesel fuel with a specific gravity of 0.86 and a viscosity of 0.048 poise (45 Saybolt seconds Universal) at 80° F. was used.

they were obtained by extrapolating the curve. Under the conditions of these tests the spray-penetration curves at 5 inches were so nearly straight that the extrapolation was permissible without introducing an appreciable error.

FACTORS AFFECTING SPRAY CHARACTERISTICS

The most important characteristics of a fuel spray from the standpoint of efficient combustion for high-speed compression-ignition engines are penetration, atomization, dispersion, and distribution. Precise definitions of these terms as applied to fuel sprays have been given by De Juhasz. (Reference 4.) The factors affecting these spray characteristics for any one combustion-chamber shape are:

1. The injection-valve design.
2. The injection pressure.
3. The physical properties of the fuel oil.
4. The physical properties of the gases in the combustion chamber.
5. Air flow in the combustion chamber.

The function of the injection valve is to so utilize all the energy supplied by the fuel pump as to obtain the proper distribution of the fuel in the combustion chamber and thus promote an efficient combustion. If the injection valve is of the closed type, a spring-loaded stem is usually employed which is lifted to permit the fuel flow through the nozzle when the pressure of the fuel is raised to a predetermined value. For a given combustion-chamber shape and a pressure-time relation in the fuel line immediately before the discharge nozzle, the design of the injection valve may be varied so as to control to some extent the penetration, atomization, dispersion, and distribution of the fuel spray.

For a fixed orifice area, engine speed, and geometrical shape of the nozzle the fuel pressure-time rela-

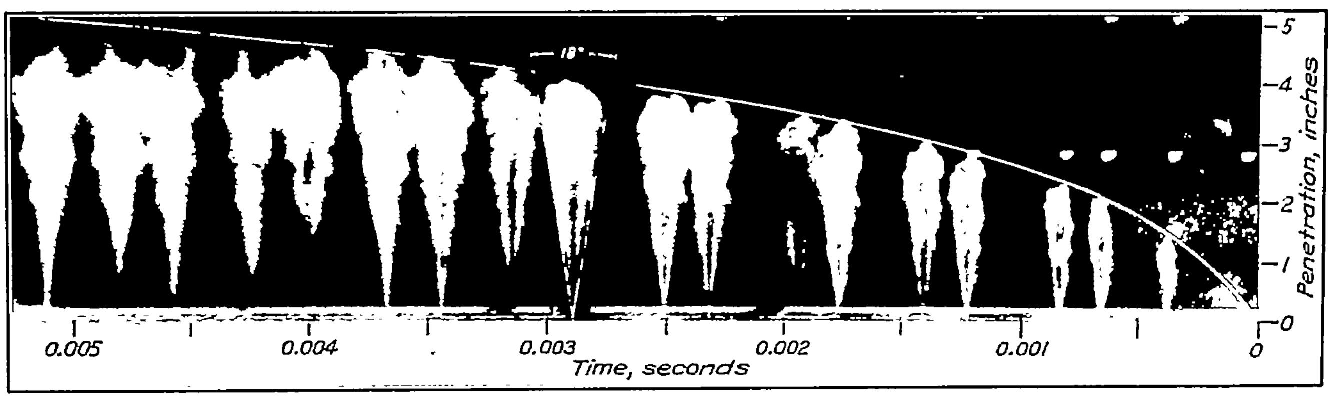


FIGURE 2.—Spray photographs with lines drawn to show spray-tip penetration and spray cone angle. Orifice length=0.056 inch; orifice diameter=0.014 inch; injection pressure=2,000 pounds per square inch; chamber air density=1.35 pounds per cubic foot. Plain stem

A record of the development of a single fuel spray is shown in Figure 2. The lines drawn on the photograph show how the spray penetration and spray cone angles were measured. The maximum penetration that the apparatus could record was slightly over 5 inches. Where greater penetrations are shown,

tion behind the nozzle depends largely upon the pump design, the elasticity of the fuel, and the length, diameter, and wall thickness of the tube connecting the pump with the injection valve. Other conditions being the same, the intensity of the pressure impulses propagated to the injection valve may be varied within wide limits by changing the design of the cam actuating the pump plunger. This effect is shown in the comprehensive treatises on this phase of the subject by Sass and by Rothrock. (References 5 and 6, respectively.)

The characteristics of the spray are influenced by the density, the viscosity, and the surface tension of the fuel, and by the density and the viscosity of the chamber gases. These three properties of the fuel are affected by variation of conditions in the combustion chamber; density and viscosity increase with pressure, and all three decrease with an increase in temperature. The density and the viscosity of the chamber gases have an effect on the penetration and atomization of the fuel sprays. The density of the gases increases with pressure and decreases with temperature, and the viscosity increases with both pressure and temperature.

Greater spray distribution may be obtained by increasing the air flow in the combustion chamber. In engines using directed air flow the practice is to design the cylinder head so as to increase the air velocities and direct the air flow past the fuel spray either tangentially or counter to the spray. The latter direction has been found to have greater effect on spray distribution.

Penetration.—A fuel spray to penetrate at a fast rate must possess, primarily, a high initial velocity along its axis and a small spray cone angle. For the same pressure-time variation in the injection system the nozzle-design features with which high initial velocity of spray can be obtained were found to be: (*a*) Smooth passages before the orifice, and (*b*) sufficient orifice length in proportion to its diameter to direct the spray along its axis. According to hydrodynamic laws, in passing from the large sectional area before the nozzle to the usually much smaller area of the orifice the jet assumes a spiral motion and a tendency to first contract and then reexpand. In this event there are forces initiated normal to the jet axis, and consequently velocity components normal to the orifice axis. The greater the spiral motion given to the jet prior to its issue in the combustion chamber the larger the cone angle of the spray produced, and consequently the greater the retardation. Therefore high penetration is obtained from a nozzle the geometrical shape of which produces a jet flow having the least contraction and the minimum amount of spiral motion. Previous experiments with larger nozzles have shown that the nearer the fluid passage before the orifice is made to approach the shape given to a Venturi nozzle the nearer these conditions of flow are approached. In a recent investigation at this laboratory by the author (reference 2) this relation was also found to be true for the range of orifice sizes employed with the high-speed compression-ignition engines. With sufficient orifice length to insure a coefficient of contraction equal to unity the Venturi type of nozzle gave the highest coefficient of discharge, and consequently the highest initial velocity.

As shown by Kuehn (reference 7) and Triebnigg (reference 8), under the injection pressures and the conditions that exist in the combustion chamber of compression-ignition engines the jet bursts into a spray of small droplets immediately after its issue from the orifice. According to a theoretically derived equation by Triebnigg, the distance at which this dissolution of the jet takes place is of the order of 0.001 inch from the outside opening of the orifice for an injection pressure of 4,000 pounds per square inch and a chamber density of 1 pound per cubic foot. Spray photographs obtained at this laboratory and other data obtained elsewhere tend to confirm these computations.

With a given initial velocity the penetration of the spray in the combustion chamber depends upon the mean diameter of the fuel drops of which the spray is composed, the physical properties of both fuel and air, and the motion of the chamber air relative to the spray. At very high spray velocities the influence of the air flow on the spray is small until after the fuel drops have lost the greater part of their initial velocity. The laws governing the motion of the individual fuel drops subsequent to the jet dissolution are therefore those of individual spheres moving in a viscous medium. Mathematical treatment of the motion of spheres in a viscous medium is given in most textbooks on the subject of fluids. Experimental or theoretical determination of the constants involved for the conditions of spray injection in combustion chambers in which a large number of fuel drops of different sizes are traveling in close proximity is not easy. Nevertheless, by studying such relations the degree to which the various factors affect the spray motion can be analyzed and better understood.

The resistance R that a spherical body encounters in its motion through a viscous fluid depends on its diameter d, its velocity V, the density ρ of the medium, and the viscosity μ of the medium. Expressed in the form of an equation (reference 9):

$$R = Kd^x\rho^y\mu^zV^w \qquad (1)$$

where K is a constant, the value of which is determined by experiment for any particular set of conditions, and x, y, z, and w are exponents, the value of which depends on the experimental conditions.

Dimensional considerations require the dimensions of each side of this equation to be the same. Therefore by equating exponents of mass M, length L, and time T, and since

$$[R]=[MLT^{-2}],\ [d]=[L],\ [\rho]=[ML^{-3}],$$
$$[\mu]=[ML^{-1}T^{-1}],\ \text{and}\ [V]=[LT^{-1}]$$
$$MLT^{-2}=L^{x}M^{y}L^{-3y}M^{z}L^{-z}T^{-z}L^{w}T^{-w}$$
$$x-3y-z+w=1$$
$$y+z=1$$
$$-z-w=-2$$
$$x=w,\ y=w-1,\ \text{and}\ z=2-w$$

So that

$$R=Kd^{w}\rho^{w-1}\mu^{2-w}V^{w}=K\left(\frac{Vd\rho}{\mu}\right)^{w}\frac{\mu^{2}}{\rho} \tag{2}$$

Experiments have shown that the value of the exponent w varies from 1 to 2, depending on the value of the Reynolds Number $\left(\frac{Vd\rho}{\mu}\right)$ of the motion. At low Reynolds Numbers the value of the exponent w was found to be equal to 1, and therefore

$$R=K\mu Vd \tag{3}$$

In equation (3) the resistance varies as the first power of the velocity, the diameter, and the viscosity of the medium and is independent of the density of the medium. Stokes found the value of K to be equal to 3π for spherical bodies. As the velocity of the moving body is increased, however, the value of w is increased, and for a short range of Reynolds Number the value of w varies between 1 and a value slightly greater than 2. In that event both the viscosity and the density of the medium influence the resistance. Finally, as the velocity is increased, a Reynolds Number is reached beyond which the value of w is equal to 2, or

$$R=KV^{2}d^{2}\rho \tag{4}$$

The resistance then varies as the square of the velocity and is independent of the viscosity of the medium. The value of K is equal to $\frac{\pi}{4}\psi$, where ψ is some function of the Reynolds Number of the motion.

At the initial fuel-drop velocities and the injection pressures under which the fuel is injected in the combustion chamber of a compression-ignition engine, the motion of the fuel drops for a short time immediately after their formation must follow the velocity square law. As their progress is retarded, however, the motion changes to the intermediate law, and finally, if not already ignited, may follow the first power, or Stokes's law. Experiments in this laboratory (reference 10) and by Bird with sprays in hot, compressed air (reference 11) tend to indicate that the value of the exponent w of equation (2) must vary between 1.5 and 2 for the greater part of the penetration of the fuel drops prior to the approach of their relative velocity to the value of zero.

While the velocity of the fuel spray is diminishing, the kinetic energy of the fuel drops composing it is partially transmitted to the surrounding air, giving the air an accelerated whirling motion in the direction of the spray motion. Thus after the fuel drops are brought to a standstill with respect to the moving air the work of distribution is continued by the whirling air, which may carry the fuel droplets to the farthest recesses of the combustion chamber. Where some degree of orderly air flow exists in the combustion chamber, the fuel drops are carried in the direction of the air motion upon losing the greater part of their initial velocity.

The rapidity with which the individual fuel drops are brought to a standstill may be better understood if the equations giving their motion are examined. For the purpose of a more simplified explanation it will be assumed that the resistance to the fuel droplets follows the velocity square law ($w=2$) during the greater part of their penetration. Somewhat different relations are obtained if the assumption is made that it follows a law varying as some power other than 2. The difference, however, is only in the degree in which the various factors of equation (2) affect retardation, the effect being always in the same direction. For $2>w>1$ (which is the range of fuel spray injection), with the departure of w from 2 and approach to 1, the effect of the density decreases and the effect of the viscosity increases on account of the term $\frac{\mu^{2}}{\rho}$.

The deceleration force on a spherical drop from the fundamental equation $f=ma$ is

$$f=\frac{\pi d^{3}\rho_{o}}{6}\,\frac{dV}{dt} \tag{5}$$

The resisting force in the medium must equal this decelerating force of the drop, or

$$\frac{\pi d^{3}}{6}\rho_{o}\frac{dV}{dt}=-\frac{\pi d^{2}}{4}\psi V^{2}\rho_{a}=-KV^{2}d^{2}\rho_{a} \tag{6}$$

where ρ_o and ρ_a are the respective densities of oil and air.

Integrating twice between the appropriate limits, the distance S the drop traversed is

$$S=\frac{1}{C}\log_{e}(CV_{o}t+1) \tag{7}$$

$$\text{or}\ S=\frac{1}{C}\log_{e}\left(\frac{V_{o}}{V}\right) \tag{7a}$$

where

$$C=\frac{3}{2}\psi\frac{\rho_{a}}{\rho_{o}}\frac{1}{d}$$

V_o is initial velocity of the drops, and V is the velocity of the drops at any time.

Solving for V in equation (7a),

$$V=V_{o}e^{-CS}$$
$$=V_{o}e^{-\frac{3}{2}\psi\frac{\rho_{a}}{\rho_{o}}\frac{S}{d}} \tag{8}$$

This relation is readily recognizable as that of a retarded motion. The equation shows that a drop of a smaller diameter will be more rapidly retarded than a drop of a larger diameter of the same initial velocity. As the greatest part of the penetration of the fuel spray is obtained when in equation (2) $w=2$, $w<2$, and $w>1$, equations (7) and (8) (and similarly derived equations with $2>w>1$) explain why it is possible to find only a small difference in the ultimate penetration between sprays from the same nozzle, but with different injection pressures. This condition was found to be true by Riehm (reference 12) for injection pressures of 1,600 pounds per square inch and lower. Spray photographs taken at this laboratory (reference 10) have shown the spray with the higher injection pressure to penetrate at first faster than a spray with a lower injection pressure, but the retardation of the first spray was greater than that of the second. A few thousandths of a second after the start of injection the spray-tip velocity was the same for injection pressure from 2,000 to 8,000 pounds per square inch. From the investigations of Sass and Kuehn it is known that the average diameter of the fuel drops diminishes with the increase of the injection pressure. It follows, then, that sprays with a higher injection pressure composed, on the average, of smaller-size drops travel faster at first than sprays with a lower injection pressure and larger-size drops. But the larger drops do not lose their velocity so rapidly and soon overtake the smaller. To assume, however, that the maximum penetration is independent of the injection pressure for widely divergent conditions is inconsistent with equation (8).

Equations (7) and (8), combined with the foregoing explanations, indicate also how the spray characteristics may vary with the time at which the spray is injected. Sprays injected at or near the end of the compression stroke when the density in the chamber is highest penetrate less, but atomize better than sprays injected in the earlier part of the compression stroke.

Atomization.—The term "atomization" is used to denote the size of the drops into which the jet breaks immediately upon its entrance into the combustion chamber. For any fuel oil and for any orifice size atomization depends almost entirely on the jet energy and on the conditions of the surrounding medium at the instant the jet dissolution takes place. From the theoretical work of Triebnigg and the experimental investigations of Kuehn, Sass, and this laboratory the magnitude of the fuel drops is known to be:

1. Proportional to—
   (a) The surface tension of the fuel oil.
   (b) The density of the fuel oil.
   (c) The diameter of the orifice.
2. Inversely proportional to the excess pressure of the fuel oil over the combustion-chamber pressure.

As the relative velocity of the fuel drops with respect to the air is rapidly reduced and as their high surface tension causes a resistance to a change in form, a further breaking up of the particles after the initial dissolution of the spray can not be expected.

Dispersion.—Spray dispersion is defined as the ratio of spray volume to oil volume discharged. The single factor by which dispersion may be influenced most is the discharge-nozzle design and the injection valve as a whole. Slightly better dispersion may also be obtained in air at high density when fuel of a low density is used. The usual nozzle designs employed to obtain good dispersion are the annular-orifice type, the slit orifice, the impinging jets, the lip nozzle, and the type employing helical grooves before the orifice. Along with good dispersion better atomization may also be obtained when the opening of the annular or slit orifices is made small, which is analogous to using small round orifices to obtain better atomization. The amount of dispersion may also be controlled within wide limits by varying the angle of the helical grooves.

A gain in the spray dispersion by varying the nozzle design, however, is always obtained at a loss in penetration. With sprays of large cross section the retardation in the combustion chamber was shown in a previous report of the committee (reference 13) to be greater than with sprays of a small cross section. With the helically-grooved-stem type of valve, especially, the normal-to-the-axis velocity is larger than that with a valve having a plain stem under the same conditions.

Distribution.—Distribution is defined as the ratio of air to fuel mixture throughout the chamber. It follows from this definition, therefore, that the penetration and dispersion of the fuel spray partially control the distribution of the fuel. The usual methods to obtain a good distribution are: (1) To produce a spray having the shape of the combustion chamber and with sufficient penetration to reach the farthest recesses of the chamber, (2) to produce sufficient orderly air flow to mix the fuel completely with the air, and (3) a combination of methods (1) and (2). The first method is used where there is not sufficient air movement in the combustion chamber to mix the air with the fuel satisfactorily. The multiorifice nozzle was found to fulfill the requirements of the first method (reference 14); for, in addition to the freedom it offers in the proper apportioning of the spray, it yields a good penetration and a better atomization than a spray from a single large orifice of the same capacity. The sizes of the orifices for a multiorifice nozzle are necessarily much smaller than for a single orifice giving the same rate of discharge. The sprays from the smaller orifices do not penetrate so rapidly as sprays from larger orifices. As shown by the experimental results of these tests, however, the difference in the rate of penetration between sprays from orifices larger than about 0.015 inch in diameter is small. Thus, although there is a small decrease in penetration when a nozzle with a single large orifice is replaced by a nozzle with several orifices of smaller size, there is a large gain in distribution, and according to Sass (reference 5) some increase in atomization.

Good results were also obtained when methods (2) and (3) were used to obtain good spray distribution. (References 15 and 16.) Regarding the use of orderly air flow, care must be exercised to obtain the proper

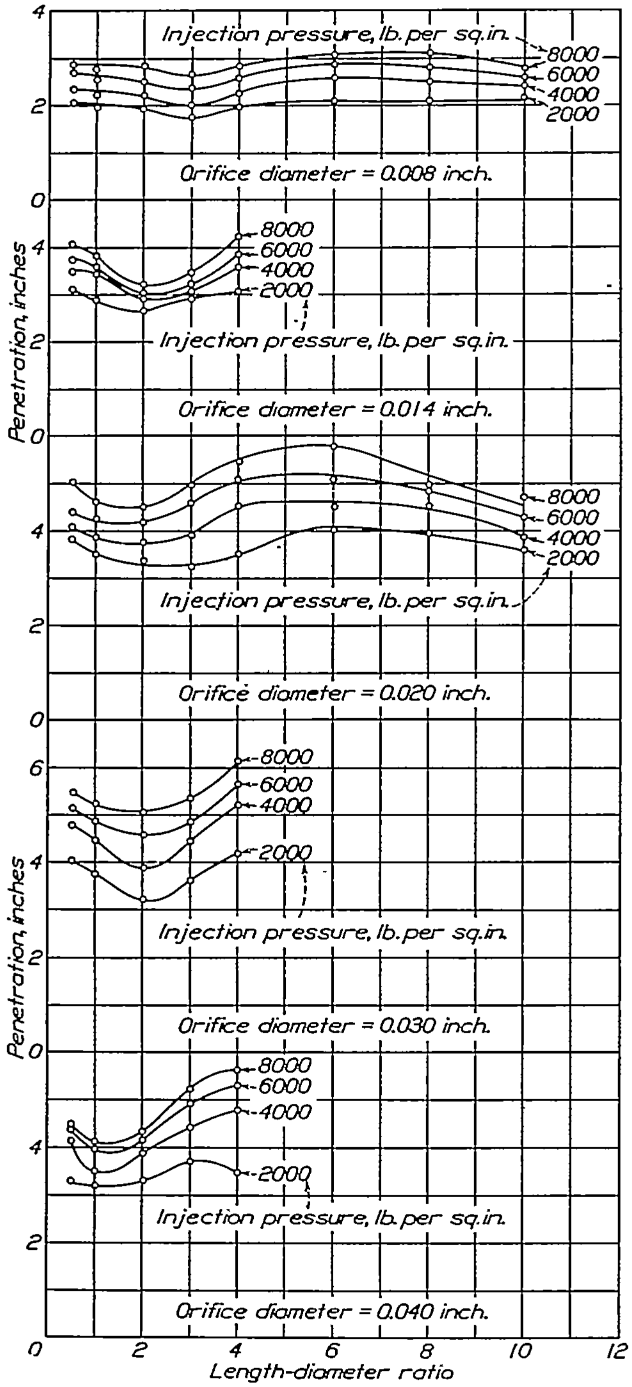


FIGURE 3.—Spray-tip penetration at varying length-diameter ratio and different sizes of discharge orifice. Penetration 0.001 second after start of injection. Plain stem. Chamber air density=0.994 pounds per cubic foot

amount of air flow conducive to good combustion. Both Ricardo and Hesselman found that combustion efficiency was increased by increasing the velocity of air flow up to a certain point beyond which poorer combustion was obtained.

RESULTS AND DISCUSSION

Sprays from plain round-orifice nozzles.—Figure 3 shows the spray penetration at 0.001 second after the start of injection plotted against orifice length-diameter ratio when a plain stem was used in the injection valve. With all the orifices there was a general tendency for the penetration to decrease, to reach a minimum, and then to increase as the length-diameter ratio was increased by small increments between the values of 0.5 and 4. The ratio at which a minimum was reached varied between 1 and 3, depending on the orifice diameter and the test conditions. The penetration with the 0.008 and 0.020 inch diameter orifices, which were tested at larger ratios, reached a maximum between the ratios of 5 and 6, and decreased again gradually as the ratio was increased further. The trend of the curves obtained with the 0.040-inch orifice indicates that a maximum penetration would have been reached at a ratio a little greater than 4, if that orifice had been tested at larger ratios. This indication leads to the conclusion that a maximum penetration would have been reached also with the 0.014 and 0.030 inch orifices between the length-diameter ratios of 4 and 6, if these orifices had been tested at larger ratios. Although the shape of the curves is the same in all cases, there is a general shifting of the ratio at which a maximum or a minimum was attained toward the origin as the orifice size was increased. There is an increase in penetration as the orifice diameter is increased to 0.030 inch and then a slight decrease with the 0.040 inch. This variation, however, is small with orifices greater than 0.014 inch in diameter. This finding is in agreement with the results obtained by Rothrock (reference 17), which show the pressure behind the nozzle to be affected slightly for the range of orifices between 0.008 and 0.030 inch, but to be reduced considerably for the 0.040-inch orifice.

In Figure 4 the penetrations 0.002 and 0.004 second after the start of injection with the 0.008-inch orifice are given. The general shape of the curves and the ratios at which a minimum or a maximum penetration was obtained are the same as for the corresponding orifice in Figure 3.

Figures 5 and 6 show the penetration at 0.001 and 0.002 second after the start of injection with the 0.014-inch-diameter orifice and different air densities. As was found in previous experimental investigations at this laboratory and as the equations (7) and (8) of the analysis indicate, the penetration decreases with the increase of density in the spray chamber. The variation in penetration with changes in the length-diameter ratio of the orifice becomes smaller with an increase of density. Owing to the limitations of the recording apparatus, the penetration at times greater than 0.001 second after the start of injection could not be recorded with orifices larger than 0.014 inch. For

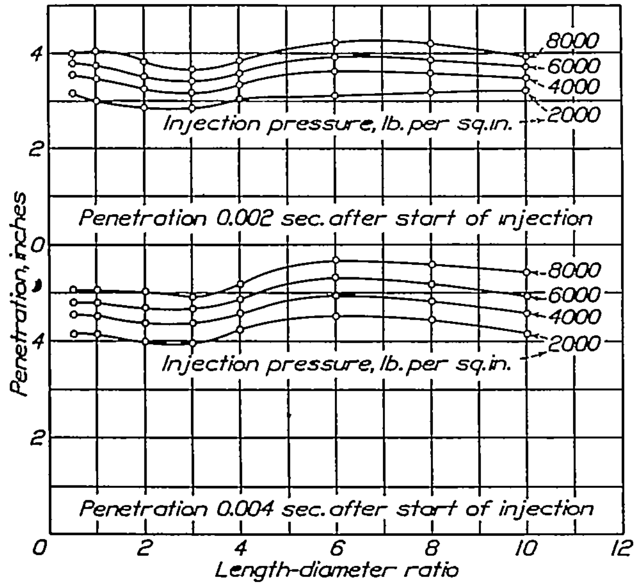


FIGURE 4.—Spray-tip penetration at varying length-diameter ratio of the 0.008-inch discharge orifice at 0.002 and 0.004 second. Plain stem. Chamber air density = 0.994 pounds per cubic foot

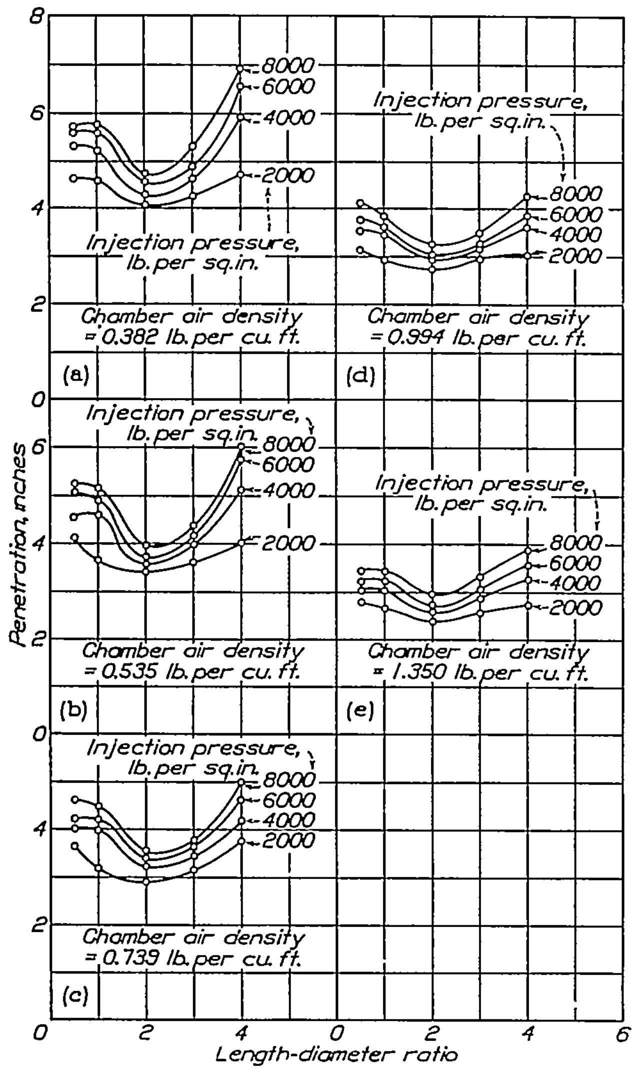


FIGURE 5.—Spray-tip penetration at varying length-diameter ratio of the 0.014-inch discharge orifice and different chamber air densities. Penetration 0.001 second after start of injection. Plain stem

the same reason the penetration for the 0.014-inch orifice could not be recorded at the two lower air densities.

In Figure 7 the results obtained with 0.040-inch-diameter orifice at various chamber air densities are given. A comparison of these curves of the 0.040-inch orifice with the corresponding curves of different densities of the 0.014-inch orifice (fig. 5) shows that the penetration with the smaller orifice is affected more by the air density than that with the larger orifice. The effect of change of density in equations (7) and (8) is greater on the penetration of the smaller drop than on the penetration of the larger drop. The test results of Sass and others have shown that the magnitude of the spray drops decreases with the decrease of orifice diameter. The spray from the larger

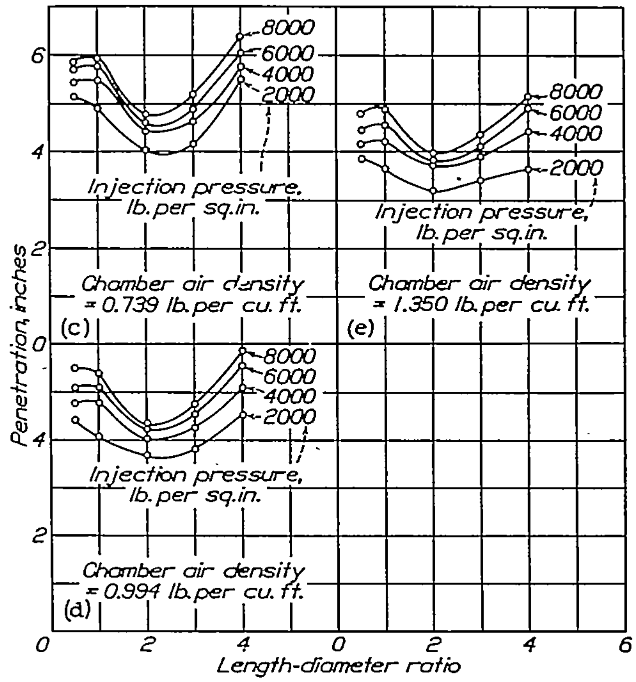


FIGURE 6.—Spray-tip penetration at varying length-diameter ratio of the 0.014-inch discharge orifice and different chamber air densities. Penetration 0.002 second after start of injection. Plain stem

orifice is therefore affected the least, because the value of the exponent of the retarding factor e in equation (8) is less than it is for the spray from the smaller orifice, which is composed, on the average, of smaller-sized drops.

In Figure 8 the coefficients of discharge (reference 18) of the nozzle with the 0.008-inch orifice at various injection pressures are given. The shape of the coefficient of discharge curves approaches that of the penetration curves for ratios greater than 4. As the ratio was increased beyond 5, the friction losses increased, and both the coefficient and the penetration began to decrease gradually.

In an investigation on the effect of length-diameter ratio on the coefficient of discharge Bird (reference 19) obtained somewhat irregular results with a 0.013-inch-diameter orifice. Owing to the high viscosity oil used, the flow through this orifice was in the semiturbulent range. In his curve of coefficient of discharge plotted against length-diameter ratio there was a depression at the ratio of about 2 followed by a rise which reached a maximum at a ratio slightly greater than 3, and then a gradual drop and a slight depression in the curve at a ratio of 7.5. These irregularities and the low coefficients that he obtained can probably be

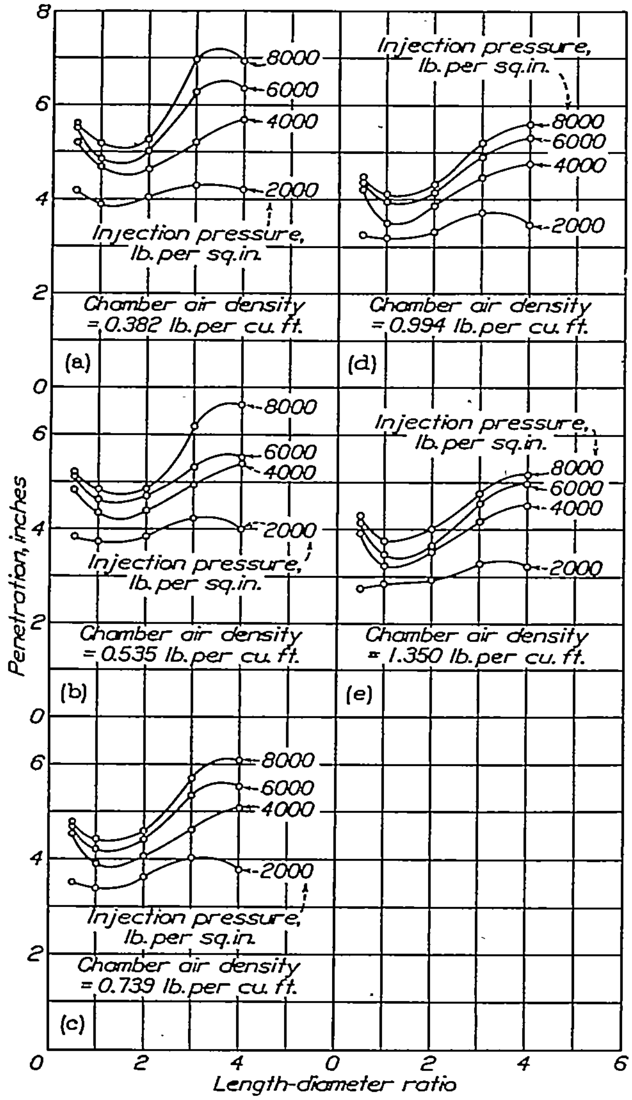


FIGURE 7.—Spray-tip penetration at varying length-diameter ratio of the 0.040-inch discharge orifice and different chamber air densities. Penetration 0.001 second after start of injection. Plain stem

attributed to the geometrical shape of the nozzle, which resulted in a different condition of flow within the nozzle than with the tests reported herein. The difference in the flow conditions may be seen by comparing curves given in Figure 9 of coefficient of discharge against Reynolds Number. These curves show that at the lower range of Reynolds Number, during which the transition from laminar to turbulent flow takes place, there was a rapid increase and then a rapid decrease in the coefficient obtained by Bird as the Reynolds Number was increased. In the results obtained at this laboratory the transition is more gradual. Bird found that the resistance to the flow through the orifice in the transitional region varied with the velocity to powers between 2 and 3.

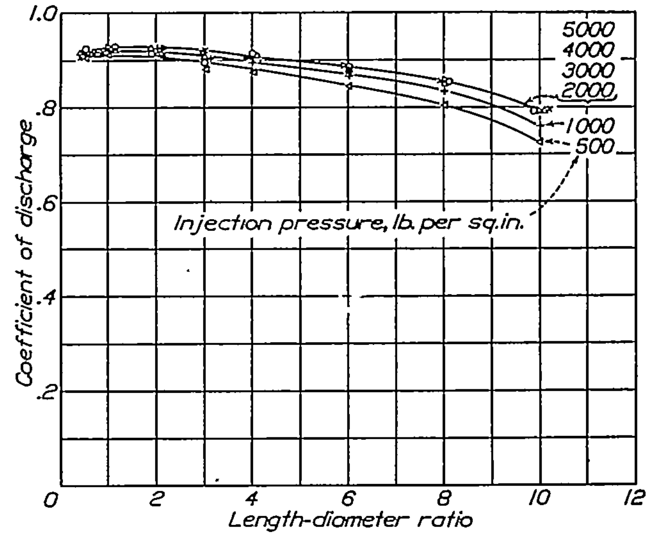


FIGURE 8.—Coefficient of discharge at varying length-diameter ratio of the 0.008-inch discharge orifice. Atmospheric chamber air density. Plain stem

The explanation of irregularities in the penetration and coefficient of discharge curves is found in an analysis of the flow through the injection nozzle. As pointed out in the analysis of the factors affecting spray characteristics, in passing from the larger sectional area to the usually much smaller area of the

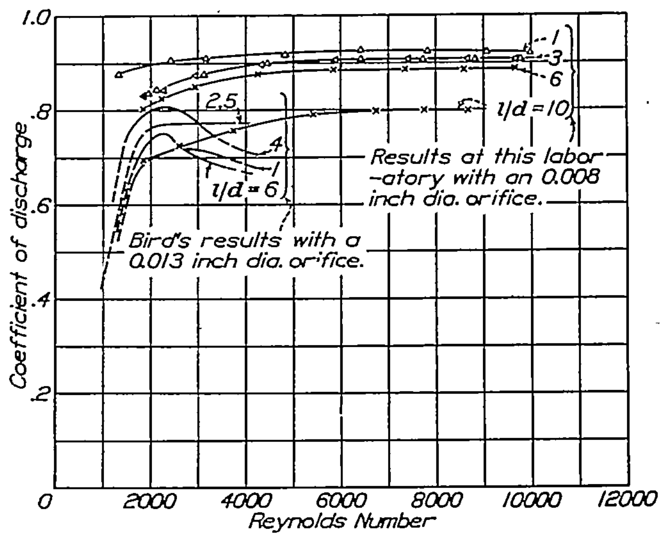


FIGURE 9.—Coefficient of discharge at varying Reynolds Number

orifice the jet is given a spiral motion and a tendency to contract; i. e., the coefficient of contraction decreases and that of velocity increases. The amount of contraction depends chiefly on the shape of the entering edge of the orifice, but is also affected by the pressure head and by the physical properties of the fuel oil. Following this contraction the jet reexpands and fills the orifice throat again. If the throat is sufficiently long, the expanded jet is redirected parallel to the axis of the orifice. The result is to decrease the velocity component of the jet perpendicular to the axis of the throat. If the length of the orifice is not sufficient to permit a complete reexpansion of the jet within the orifice throat, a spray is obtained with the fuel particles having a perpendicular motion as well as axial, which condition results in a smaller penetration.

The presence of a maximum penetration at length-diameter ratios greater than 3 is explained by the fact that at the larger length-diameter ratios the friction losses become appreciable. (Reference 18.) Increasing the orifice length beyond that at which the jet is fully reexpanded increases also the friction losses. Hence a ratio must be reached beyond which the friction loss within the orifice more than counterbalances the increase in penetration obtained by increasing the orifice length, and the result is a reduction in penetration.

From the test results presented and from the foregoing discussion it is seen that with round-orifice nozzles the length-diameter ratio of the orifice must be between 4 and 7 if a high spray penetration and a high coefficient of discharge are desired. The ratio to be used for the nozzle shapes of these tests is between 4 and 5 for orifices ranging from 0.030 to 0.040 inch in diameter and between 5 and 6 for orifice sizes less than 0.030 inch in diameter.

An analysis of the experimental results for the variation of the spray-tip deceleration with velocity, $a = KV^n$, gave the values of n shown in Table I. The motion of the spray tip was investigated for each spray only at the ratios of maximum and minimum penetration. As seen from the table, the deceleration of the spray tip, and thus the resistance of the motion as shown in the analysis, varies as some power between the first and second of the velocity.

TABLE I.—VARIATION OF SPRAY-TIP DECELERATION WITH VELOCITY

Spray No.	Orifice diameter	Injection pressure	Chamber density	$\frac{l}{d}$	n
	In.	*Lb./sq. in.*	*Lb./cu. ft.*		
1	0.008	2,000	0.994	6	1.10
2	.008	8,000	.994	6	1.15
3	.008	2,000	.994	3	1.40
4	.008	8,000	.994	3	1.60
5	.020	2,000	.994	6	1.20
6	.020	8,000	.994	6	1.90
7	.020	2,000	.994	3	1.00
8	.020	8,000	.994	3	1.50

Centrifugal sprays.—In Figures 10 and 11 is given the spray-tip penetration with the orifices tested 0.002 and 0.004 second after the start of injection when a helically grooved stem was used in the injection valve. With the exception of the 0.030-inch-diameter orifice, the penetration increased as the length-diameter ratio of the orifice was increased from 0.5 to 4. The penetration with the 0.008 and 0.020 inch orifices, which were tested for higher ratios, reached a maximum at a ratio of about 7 and 5, respectively. The decrease in penetration after the maximum is much slower than when the plain stem was used in the injection valve. This decrease is obviously due to the smaller

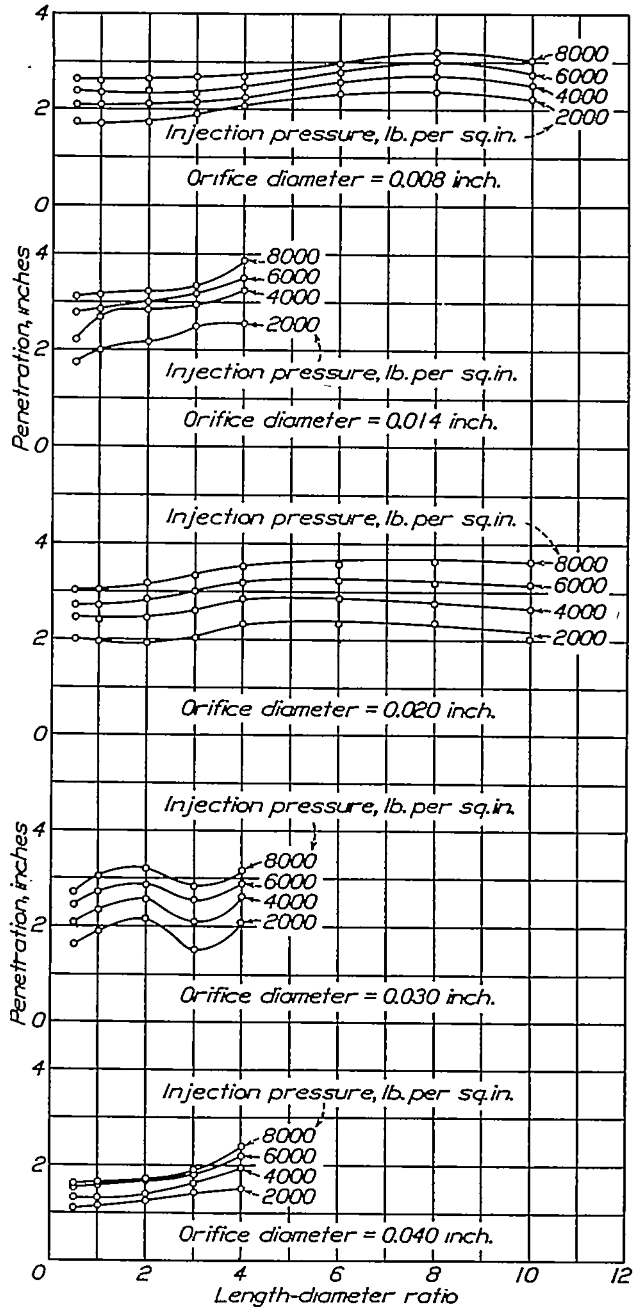


FIGURE 10.—Spray-tip penetration at varying length-diameter ratio and different sizes of discharge orifice. Penetration at 0.002 second after start of injection. Helically grooved stem. Chamber air density=0.994 pound per cubic foot

velocity of flow and the smaller consequent losses of energy within the orifice throat. No explanation can be given for the sinusoidal appearance of the penetration curves with the 0.030-inch-diameter orifice. This phenomenon is not evident with any other orifice. Tests by Joachim and Beardsley (reference 13) for length-diameter ratios between 0.2 and 2.6 with a 0.022-inch-round orifice and with 40° helix angle of the grooves gave substantially the same shape of curve as that obtained with the 0.030-inch orifice of this investigation. Apparently there must be a ratio of orifice area to groove area for any given helix angle of

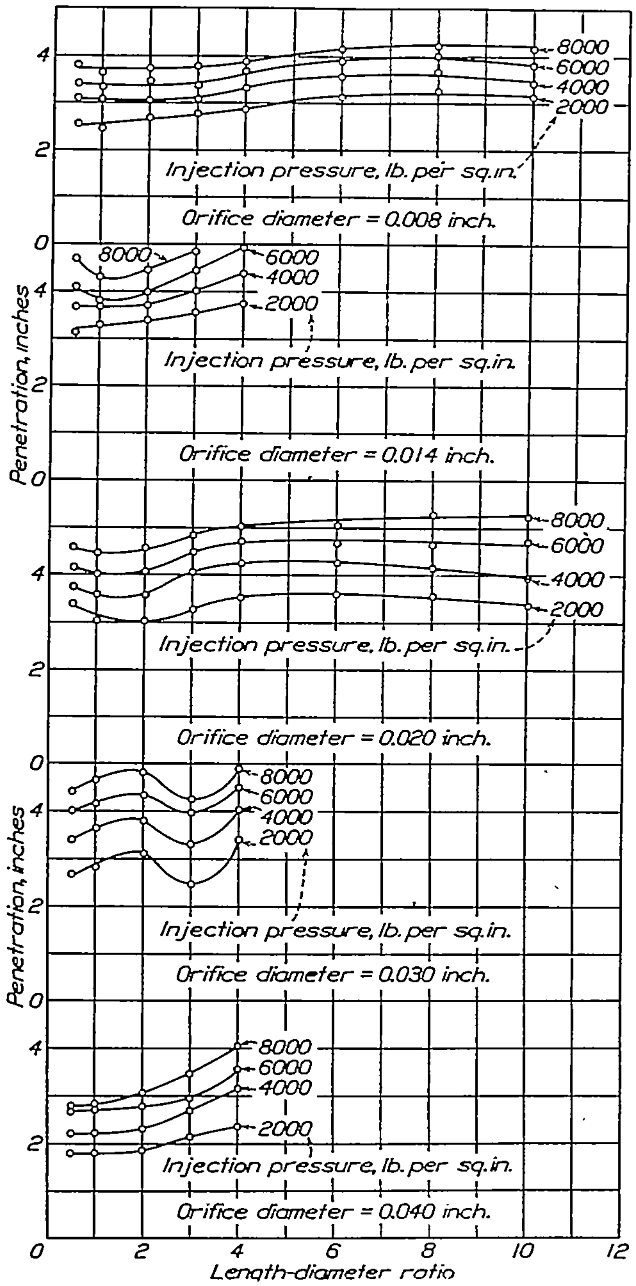


FIGURE 11.—Spray-tip penetration at varying length-diameter ratio and different sizes of discharge orifice. Penetration 0.004 second after start of injection. Helically grooved stem. Chamber air density=0.994 pound per cubic foot

the grooves at which the flow conditions in the nozzle, at least for the lower length-diameter ratios, are different than for any other combination of areas.

A comparison of the curves obtained when a plain stem was used in the injection valve (figs. 3, 4, 5, 6, and 7) with the curves when a helically grooved stem was used (figs. 10 and 11) shows that the penetration with the centrifugal sprays was considerably smaller. This smaller penetration is largely due to the nonaxial motion given to the spray particles and to the loss of energy caused by the fuel passing through the restricted helical grooves and the subsequent reconverging in entering the orifice. In passing through the grooves the fuel was given a velocity component tangential, as well as axial, to the cross section of the injection-valve stem. Following this action the fuel was forced to converge and pass through the orifice, where the axial component was increased and the tangential component partially damped out. The amount of this damping depended upon the ratio of orifice length to diameter and upon the ratio of orifice area to groove area. As the orifice length was increased with respect to diameter the tangential-velocity component of the particles was further decreased, which resulted in an increase in the penetration. As the ratio of orifice area

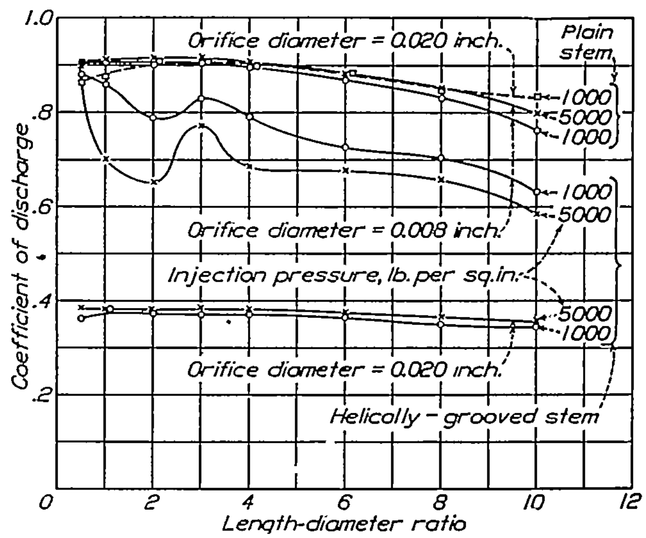


FIGURE 12.—Comparison of coefficients of discharge with a plain and with a helically grooved stem. Atmospheric chamber air density

to groove area was increased the tangential-velocity component of the fuel particles was increased, because the velocity through the helical grooves was increased. This increase in tangential velocity caused the sprays from the larger orifices to have less penetration than the sprays from the smaller orifices.

An indication of the extent of the energy losses in the injection valve when a helically grooved stem is used can be obtained by comparing the coefficient-of-discharge curves given in Figure 12. These curves were taken from reference 18 and give the coefficients of discharge for the nozzles of the present tests. The area of the orifice cross section was used in computing the coefficient. The larger losses occur with the larger orifice because the velocity through the grooves and consequently the friction and the tangential component of the fuel particles are larger. Large irregularities were observed in the values of the coefficient for the 0.008-inch orifice with the helically grooved stem at the lower length-diameter ratios of the orifice.

No such irregularities in the coefficient of discharge were observed with any of the other orifices tested, varying in size from 0.014 to 0.040 inch in diameter. (Reference 18.) The effect of the reduced coefficient of discharge when a helically grooved stem was used can be seen in the penetration curves obtained with the same valve setting and injection pressures. The penetration, as well as the coefficient of discharge, is considerably reduced as the tangential velocity component given to the fuel particles is increased by the use of a helically grooved stem.

Spray cone angle.—In Figure 13 are given the spray cone angles 0.003 second after the start of injection, when the spray was fully developed. With the plain stem the spray cone angle varied from 15° to 25°, depending on the orifice size and the length-diameter ratio. For any one orifice and length-diameter ratio of the orifice the angle was about the same, regardless of the injection pressure and chamber density at which the orifices were tested. A comparison of Figures 3, 4, 5, 6, and 7 with Figure 13 shows the penetration with the plain stem to decrease and the spray angle to increase at the lower length-diameter ratios of the orifice, at which an unstable jet contraction region exists. The angle increased and then again decreased as the ratio was increased from 0.5 to 4. For ratios greater than 4 the angle remained practically constant with the 0.008 and 0.020 inch orifices, which were tested at these higher ratios.

With the helically grooved stem the spray cone angle varied from 20° to 70°, depending on the orifice size and the length-diameter ratio tested. The angle increased with the increase of orifice size. This increase was due to the larger tangential velocity given to the spray, combined with the smaller amount of reconverging of the jet with the larger-sized orifices. A radical variation in the spray cone angle can be observed with the 0.030-inch orifice. A comparison of the spray-cone-angle curve with the corresponding penetration curves of Figures 10 and 11 for the same orifice shows that an increase in the penetration resulted in a decrease in spray cone angle, and a decrease in penetration had the opposite effect. The same tendency is also observable with the other orifices tested, but it is not so pronounced as that with the 0.030-inch-diameter orifice.

CONCLUSIONS

The conclusions drawn from the experimental data are as follows:

1. With the plain stem in the injection valve, for the shape and range of orifice sizes tested:
   - (a) The length-diameter ratio giving the greatest spray-tip penetration and coefficient of discharge was found to be between 4 and 6, depending on the orifice diameter.
   - (b) For ratios less than 4 the penetration decreased and then increased as the ratio of 0.5 was approached.
   - (c) For ratios greater than 6 the friction losses due to the excessive orifice length become appreciable and penetration and coefficient of discharge decrease.
   - (d) The spray cone angle was not affected by an increase of the length-diameter ratio for ratios greater than 4, but varied with ratios of less than 4.

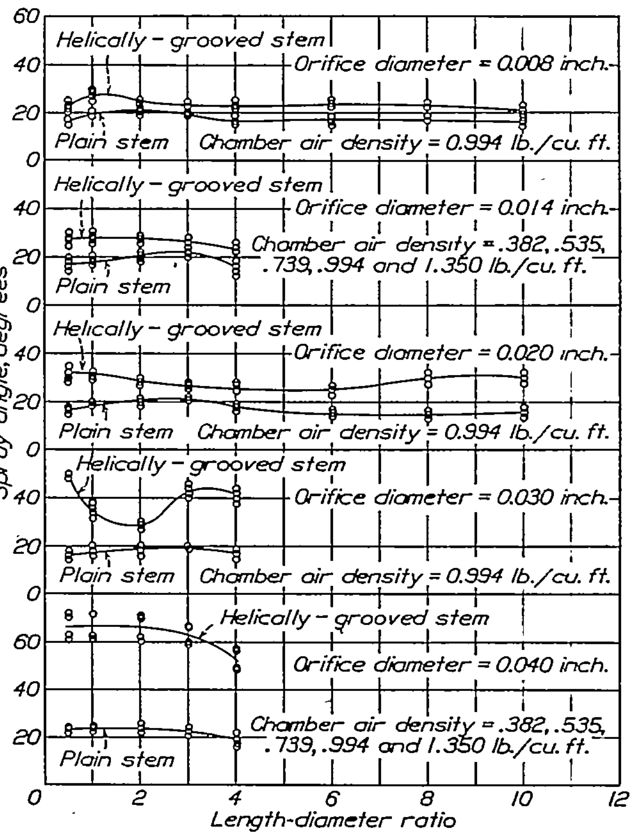


FIGURE 13.—Spray angle at varying length-diameter ratio and different sizes of discharge orifice. Injection pressure=2,000, 4,000, 6,000, and 8,000 pounds per square inch

2. With the helically-grooved stem in the injection valve:
   - (a) With the exception of the results of the 0.030-inch orifice, maximum penetration was reached at an orifice length-diameter ratio of between 5 and 7. A further increase in the ratio after the maximum resulted in a gradual decrease in penetration. The rate of change of penetration, however, was less with this stem than with the plain.
   - (b) With the exception of the 0.030-inch diameter orifice, the spray cone angle increased with the orifice-area to groove-area ratio. A maximum angle of about 70° was obtained with the 0.040-inch orifice, and a minimum of about 20° with the 0.008-inch orifice.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *May 27, 1931.*

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